Geomorphological Characteristics of the Coexisting Area of Barchan and Parabolic Dunes in the Western Hunshandake Sandy Land: A Postprint

Authors: Ren Xiaozong, Wang Songsong, Wang Yamei, Luo Jin-Hong, Ma Yongtao

Date: 2024-03-01T00:00:00+00:00

Abstract

Crescent dunes and parabolic dunes can transform into each other and coexist. Research on the geomorphological characteristics of their coexistence zones contributes to understanding their formation mechanisms and provides scientific basis for sand fixation and desertification control. Based on Esri historical imagery service, this study extracted dune morphological parameters and calculated migration directions and speeds for the coexistence zone of crescent and parabolic dunes in western Hunshandake Sandy Land across three periods (January 15, 2008; June 4, 2011; and September 20, 2016). The results indicate that typical crescent dunes are concentrated in 15 regions associated with dry lake basins in the western part of the sandy land, while incipient crescent dunes and incipient parabolic dunes are distributed sequentially around the peripheries of dry lake basins. The emergence of dry lake basins is a key factor for the development of typical crescent dunes in Hunshandake Sandy Land, and desertification caused by lake desiccation should receive adequate attention. Analysis of the most typical Region 5 in the coexistence zone reveals that typical crescent dunes and incipient crescent dunes exhibit significant differences from incipient parabolic dunes in the distribution patterns of morphological parameters related to their lateral wings. Further correlation analysis among dune morphological parameters demonstrates that during the transformation from crescent dunes to parabolic dunes, changes in windward slope length, leeward slope length, and base area are inherited, while the lateral wings undergo the most substantial changes. Additionally, the migration directions of the three dune types show minor numerical differences and are consistent with changes in the resultant drift direction (RDD), but their migration speeds differ significantly, and the factors influencing the migration speeds vary among different dune types. Vegetation has the most pronounced effect on incipient parabolic dunes with relatively good vegetation coverage, as evidenced by their migration speed being consistent with the NDVI variation trend of the sandy land during the same period. In contrast, wind speed has a more significant impact on typical crescent dunes and incipient crescent dunes with lower vegetation coverage, as their migration speeds align with the variation trends of drift potential (DP) and resultant drift potential (RDP) during the same period. Furthermore, topography, sand sources, and human activities all influence the morphology and migration of dunes in the coexistence zone.

Full Text

Geomorphologic Characteristics of the Coexistence Zone of Barchan and Parabolic Dunes in Western Hunshandake Sandy Land

REN Xiaozong, WANG Songsong, WANG Yamei, LUO Jinhong, MA Yongtao

(Taiyuan Normal University, School of Geographical Sciences, Jinzhong 030619, Shanxi, China)

Abstract

Barchan and parabolic dunes can transform into each other and coexist in the same area, resulting in a unique landscape where typical barchan dunes coexist with embryonic barchan and parabolic dunes. Understanding their spatial distribution, morphological characteristics, and migration patterns is essential for implementing targeted desertification prevention and control measures. Based on Esri' s historical image service (World Imagery Wayback), we extracted morphological parameters of dunes in the barchan-parabolic dune coexistence zone in western Hunshandake Sandy Land for three periods: January 15, 2008, June 4, 2011, and September 20, 2016, and calculated dune migration direction and velocity. Results indicate that typical barchan dunes are concentrated in 15 areas associated with dry lake beds in the western part of the sandy land, whereas embryonic barchan and parabolic dunes are sequentially distributed around the periphery of these dry lake beds. The formation of dry lake beds was a key factor in the development of typical barchan dunes in the Hunshandake Sandy Land. Therefore, greater attention should be paid to desertification caused by lake drying. Analysis of morphological parameters in the fifth zone—the most typical coexistence area—reveals significant differences between typical barchan dunes, embryonic barchan dunes, and embryonic parabolic dunes. Correlation analysis shows that windward slope length, lee slope length, and base area are inherited during transformation from barchan to parabolic dunes, with wings experiencing the greatest changes. Furthermore, the three dune types show similar migration directions but varying velocities, influenced by different factors. Vegetation cover most significantly affects embryonic parabolic dunes, which have relatively high vegetation cover, with velocity variations consistent with NDVI trends during the same period. Wind speed most significantly affects typical and embryonic barchan dunes, which have relatively low vegetation cover, with velocity variations consistent with DP and RDP trends. Additionally, terrain, sand sources, and human activities also influence the morphology and migration of barchan-parabolic dunes.

Keywords: barchan dunes; parabolic dunes; coexistence; morphology and migration; Hunshandake Sandy Land

Introduction

Barchan and parabolic dunes are two common dune types that can transform into each other and produce transitional forms under the influence of climate change or human factors. This transformation creates a unique landscape where typical barchan dunes, embryonic barchan dunes, and embryonic parabolic dunes coexist in the same area. Various factors, including vegetation, climate, wind conditions, human activities, and groundwater salinization, can drive transformations between barchan and parabolic dunes, though specific causes differ across regions. Clarifying dune types, spatial distribution, morphological characteristics, migration patterns, and underlying causes in specific coexistence zones is crucial for implementing precise desertification prevention and control measures and serves as an important basis for formulating rational land-use policies.

Previous research has shown that parabolic dunes generally evolve from barchan or transverse dunes, and can transform back into barchan or transverse dunes under conditions of vegetation degradation. The direct cause of mutual transformation is vegetation change, with increased vegetation growth rates leading to conversion of barchan dunes into parabolic dunes. Numerical simulations reveal that this transformation occurs when the erosion-deposition rate on dune surfaces decreases to less than half of the vegetation growth rate. Vegetation changes are also climate-related, with active periods of barchan-to-parabolic dune transformation corresponding to periods of higher summer temperatures, while dune reactivation corresponds to dry and cold summer periods. Wind energy environments also play an important role, with reduced wind strength favoring vegetation development.

Study Area Overview

The Hunshandake Sandy Land is located in the eastern part of the Inner Mongolia Plateau, within the farming-pastoral transition zone and the loess boundary belt of northern China. The sandy land spans approximately 125 km from north to south and about 450 km from east to west. The northern part consists of the flat Xilingol Grassland, the western part extends to the central Erlian Basin, and the southern and eastern parts are surrounded by mountains. The southern part comprises the eastern extension of the Yinshan Mountains, while the eastern part is the southern section of the Greater Khingan Range. Topographically, the sandy land features a northwest-low, southeast-high pattern, with elevations gradually rising from about 1000 m in the northwest to approximately 1300 m in the southeast. Climatically, the region belongs to the north temperate arid and semi-arid climate zone, with annual precipitation decreasing from about 450 mm in the southeast to about 150 mm in the northwest, and mean annual temperatures ranging from 1.75 to 3.23°C. The prevailing wind direction is northwest, with 50-70 windy days per year.

The eastern part of the sandy land is dominated by fixed dunes, mostly in the form of sand ridges and parabolic dunes, with abundant water resources and multiple rivers developing from the interior, where lake water is primarily fresh. In contrast, the western part is characterized by semi-fixed and mobile dunes, with relatively scarce water resources and numerous dry or semi-dry saline lakes.

Data Sources and Research Methods

2.1 Data Sources Satellite imagery was obtained from Esri' s World Imagery Wayback service, which primarily includes high-resolution imagery products from SPOT5 and other satellites with spatial resolutions ranging from 0.31 to 2.5 m, sufficient for dune morphological measurements. Wind data were derived from meteorological data products provided by the National Climatic Data Center (NCDC) in the United States, with a sampling frequency of 3 hours, wind direction data measured clockwise from true north at 1° intervals, and wind speed precision of 0.1 $m \cdot s^{-1}$.

2.2 Research Methods Historical images were loaded into ArcGIS in chronological order, and measurement tools were used to extract morphological parameters for corresponding periods, including windward slope length (L_U), lee slope length (L_D), wing width (W), south wing length (L_S), north wing length (L_N), and base area (S). It should be noted that embryonic parabolic dunes have a unique morphology, featuring both downwind-pointing wings similar to barchan dunes and upwind-pointing wings characteristic of parabolic dunes. In this study, the wing length of embryonic parabolic dunes was measured as the sum of both components, and wing width was measured as the distance between the downwind-pointing barchan-like wing tips.

The overall migration speed and direction of dunes were determined using the five-point average method, which characterizes dune movement using the migration distances and directions of five characteristic points: the windward front, dune crest, lee slope bottom, south wing, and north wing. The overall migration speed was calculated as the average of the migration distances of these five points divided by the time interval between two images, while the overall migration direction was calculated as the average of the migration directions of the five points.

Results

3.1 Spatial Distribution of Dunes in the Coexistence Zone Satellite imagery reveals that the western part of the Hunshandake Sandy Land contains numerous patchily distributed barchan-parabolic dune coexistence zones. The dune types include typical barchan dunes, embryonic barchan dunes, and embryonic parabolic dunes, which are primarily distributed in clustered patterns within 15 regions, with extensive parabolic dunes distributed continuously to the east of their periphery and large areas of semi-fixed honeycomb dunes to the west. The central axes of all dune types in the coexistence zone are approximately oriented in a northwest-southeast direction, with wing angles located on both sides (south and north wings). Each dune type exhibits distinct morphological differences.

Typical barchan dunes (Type A) present a crescent shape in plan view, are generally located in the core area of dry lake beds, have relatively long and often asymmetric wings pointing downwind, and are associated with white salt crusts exposed on nearly dry lake beds. Embryonic barchan dunes (Type B) have a more rounded planform than typical barchan dunes, with short and thick wing angles. In addition to downwind-pointing south and north wings, they also exhibit inconspicuous upwind-pointing wings. Embryonic parabolic dunes (Type C) have well-developed upwind-pointing wings while retaining portions of downwind-pointing wings, with relatively fragmented windward slopes that intermix with vegetation, making their boundaries indistinct.

3.2 Morphological Characteristics of Dunes in the Coexistence Zone We selected the fifth zone—the most typical coexistence area—for detailed morphological extraction using satellite imagery from three periods (January 15, 2008; June 4, 2011; and September 20, 2016), with a time span exceeding 8 years. A total of 82 dunes were obtained, including 9 typical barchan dunes, 35 embryonic barchan dunes, and 38 embryonic parabolic dunes. During the study period, no transformation of dune types occurred, but the morphological parameters of individual dunes changed. Statistical values for each dune type across the three periods are presented in Table 1.

Box plots were used to analyze the morphological parameters of each dune type, revealing different temporal changes in median values. The median windward slope length increased, wing width decreased, base area decreased slightly, and lee slope length showed a trend of first decreasing then increasing. The south and north wings exhibited the most outliers, indicating complex changes. Comparisons of synchronous morphological parameters among dune types showed that the medians of windward slope length and base area followed the order: typical barchan dunes > embryonic barchan dunes > embryonic parabolic dunes. For lee slope length and wing width, the order was: embryonic parabolic dunes > typical barchan dunes > embryonic barchan dunes. Additionally, embryonic parabolic dunes had the largest median south and north wing lengths, though with numerous outliers.

Bivariate diagrams plotting each morphological parameter against time for all dune types, with arrowed lines connecting values from the three periods, visually reflect temporal changes in dune parameters (Figure 4). Unlike box plots that show overall statistical patterns, these diagrams effectively indicate individual dune parameter changes over time and reflect temporal changes in bivariate relationships. The results show that base area versus windward slope length and base area versus wing width exhibit approximately linear distributions, while other parameter relationships, particularly those involving south and north wings, lack such linear characteristics.

Further correlation analysis revealed that during the same period, without distinguishing dune types, correlations between dune morphological parameters remained relatively stable across periods (Figure 5). When distinguishing dune types, the correlations of base area with windward slope length and wing width were strong for all three types. However, lee slope length showed strong correlation with windward slope length but weak correlation with wing width. Additionally, embryonic parabolic dunes exhibited strong correlation between south and north wing lengths (Figure 6). Whether distinguishing dune types or not, correlations from periods 2 and 3 were similar and generally higher than those from period 1.

3.4 Migration Characteristics of Dunes in the Coexistence Zone
Based on satellite imagery from periods 1 and 2, the average migration direction and velocity of dunes in the coexistence zone were obtained (Tables 2 and 3). During period 1 (2008-2011), the average migration directions of different dune parts were relatively consistent, with an overall average migration direction of 124.6°, approximately southeast. During period 2 (2011-2016), the average migration directions of different parts remained similar but shifted southward compared to period 1, with an overall average migration direction of 133.6°, between southeast and south-southeast. The dune crest showed the most significant southward shift. Polar coordinate analysis revealed that the windward front had more concentrated migration directions relative to other parts.

In contrast to migration direction, migration velocities differed significantly among dune parts within the same period (Figure 7). The dune crest had the highest migration velocity in both periods (Table 3). During period 1, the migration velocities of different dune types were similar, with an average of 3.51 $m \cdot yr^{-1}$. During period 2, typical and embryonic barchan dunes migrated significantly faster than embryonic parabolic dunes, with average velocities of 3.37 $m \cdot yr^{-1}$ and 2.60 $m \cdot yr^{-1}$, respectively. Comparisons of migration velocities among dune types showed that typical and embryonic barchan dunes experienced slight increases, while embryonic parabolic dunes showed a clear decrease in velocity.

Discussion

4.1 Influence of Dry Lake Beds on the Distribution Pattern The barchan-parabolic dune coexistence zone highly overlaps with dry lake bed distribution, likely related to regional salinity differences and resulting vegetation differentiation. Areas around dry lake beds have high salinization levels that limit vegetation growth, preventing the development of vegetation-dependent parabolic dunes and instead favoring barchan dunes, which are characteristic of low vegetation cover. This aligns with the observation that barchan dunes only appear in areas with sparse vegetation. Previous studies have shown that the Hunshandake Sandy Land hosted large ancient lakes during the Holocene and even Pleistocene, when the climate was much more humid than today. However, under recent climate change and human impacts, the lake area in the sandy land has rapidly shrunk, particularly in the ecologically fragile and sensitive western region. Satellite image analysis reveals that a water body present in 2008 had become a white salt crust by 2011. In addition to the interior of the sandy land, Hurchin Lake on the northern margin has also experienced rapid area reduction with obvious salinization, providing abundant sand sources and conditions for barchan dune development. Barchan dunes have already appeared locally, such as in area A on the southwestern edge of Hurchin Lake.

4.2 Influence of Vegetation on Dunes in the Coexistence Zone Dune types in the Hunshandake Sandy Land are closely related to vegetation cover. Macroscopically, the western region where the coexistence zone is located has low vegetation cover, generally less than 10%, and is dominated by mobile and semi-fixed barchan and parabolic dunes. In contrast, the central and eastern regions have relatively higher vegetation cover (10%-30%) and are dominated by fixed and semi-fixed parabolic dunes, honeycomb dunes, sand ridges, beam-nest dunes, shrub-coppice dunes, and fixed dunes. Microscopically, vegetation is the key factor in forming parabolic dunes. Changes in climate or human land-use patterns improve vegetation conditions on dune surfaces, initially growing in the wings where wind erosion and deposition are relatively weak. As vegetation gradually proliferates, it not only acts as a barrier to wind-blown sand but also fixes sand through its root system. Under this dual effect, the migration velocity of dune wings becomes slower than that of the dune core, eventually leading to the core advancing ahead of the wings, wing direction reversal pointing upwind, and formation of parabolic dunes with wings opposite to the original barchan dunes.

Vegetation condition also significantly influences dune migration. According to previous research, vegetation cover in the Hunshandake Sandy Land increased during 2008–2016. However, the impact of this overall vegetation improvement on migration velocity differs among dune types. Because typical and embryonic barchan dunes have low vegetation cover, they are less affected by vegetation changes, and their overall migration velocity did not significantly decrease. In contrast, embryonic parabolic dunes, with relatively good vegetation cover, were significantly affected, showing decreased migration velocity consistent with the overall vegetation improvement. NDVI analysis revealed that vegetation cover in the study area increased during period 2, and embryonic parabolic dunes exhibited decreased migration velocity consistent with NDVI trends (Figure 8).

4.3 Influence of Wind Conditions on Dunes in the Coexistence Zone Wind conditions represent another key factor affecting dune morphology and migration velocity. Barchan dunes generally appear in wind environments with RDP/DP > 0.7. Using wind direction and speed data from the Erlianhot meteor station upwind of the study area, we calculated the sand drift potential (DP), resultant drift direction (RDD), and resultant drift potential (RDP). The results showed that RDP/DP increased from 0.83 in period 1 to 0.93 in period 2, indicating a shift from low to medium wind energy environment. The increase in RDP/DP also suggests that the resultant drift direction shifted southward, consistent with the actual migration direction of all dune types. The higher RDP/DP values satisfy the developmental environment for typical barchan dunes.

While increased wind energy should promote dune migration, the actual situation shows different impacts on different dune types. For typical and embryonic barchan dunes with sparse vegetation cover, increased DP and RDP corresponded to increased migration velocity, showing consistent trends. However, embryonic parabolic dunes did not show increased migration velocity with RDP/DP but instead decreased due to increased vegetation cover, indicating that wind energy environment is less significant than vegetation for embryonic parabolic dune migration.

4.4 Influence of Other Factors on Dunes in the Coexistence Zone In addition to the aforementioned factors, terrain, sand sources, and human activities also significantly influence dunes in the coexistence zone, particularly for individual dunes in local areas. Terrain can substantially alter dune morphology. For instance, geophysical studies of large dunes in the Badain Jaran Desert have shown that underlying topography plays a key role in forming large sand mountains. In the Hunshandake Sandy Land, since barchan dunes are distributed in dry lake beds, terrain gradually rises from the center to the periphery. When dunes are located in areas with dramatic topographic changes, dune morphology often changes accordingly. Numerical simulations have confirmed that dunes climbing slopes become asymmetric due to terrain effects.

Typical barchan dunes generally form in areas with limited sand supply. Although the study area is not located at desert margins with low sand supply, the surrounding environment, particularly the upwind area dominated by fixed and semi-fixed parabolic dunes, provides a low sand supply environment ideal for barchan dune development. Additionally, human impacts on the coexistence zone have dual effects: on one hand, overgrazing and other activities may cause vegetation degradation and parabolic dune activation; on the other hand, rational sand control engineering can gradually stabilize barchan dunes, and such semi-fixed barchan dunes are common in the Hunshandake Sandy Land.

Conclusion

The barchan-parabolic dune coexistence zone in western Hunshandake Sandy Land includes three types: typical barchan dunes, embryonic barchan dunes, and embryonic parabolic dunes. Based on analysis of historical imagery from the World Imagery Wayback service, the following conclusions are drawn:

1) The coexistence zone is concentrated in 15 regions in western Hunshandake Sandy Land, each containing dry lake beds. The emergence of dry lake beds causes local salinization, limits vegetation growth and the development of associated parabolic dunes, and ultimately leads to the formation of barchan dunes. This is the key factor determining the distribution pattern of the coexistence zone. Therefore, greater attention should be paid to dune activation caused by lake drying and salinization in desertification control efforts.

2) Analysis of the most typical fifth zone reveals that all dune types show clear temporal trends in windward slope length, wing width, base area, and lee slope length, with medians showing increase, decrease, slight decrease, and decrease-then-increase patterns, respectively. However, changes in south and north wings are more complex, with the most outliers. Correlation analysis indicates that the south and north wings undergo the greatest changes, while windward slope length, lee slope length, and base area show inheritance during the barchan-to-parabolic dune transformation.

3) The three dune types show similar migration directions that are consistent with changes in RDP direction, but their migration velocities differ significantly, primarily influenced by vegetation and wind speed, with different effects on different dune types. Vegetation cover most significantly affects embryonic parabolic dunes with relatively good vegetation conditions, showing velocity trends consistent with NDVI. Wind speed most significantly affects relatively bare typical and embryonic barchan dunes, showing velocity trends consistent with DP and RDP. Additionally, terrain, sand sources, and human activities also influence the morphology and migration of dunes in the coexistence zone.

References

[1] Yan N, Baas A C W. Parabolic dunes and their transformations under environmental and climatic changes: Towards a conceptual framework for understanding and prediction[J]. Global and Planetary Change, 2015, 124: 123-148.

[2] Yan N, Baas A C W. Environmental controls, morphodynamic processes, and ecogeomorphic interactions of barchan to parabolic dune transformations[J]. Geomorphology, 2017, 278: 209-237.

[3] Livingstone I, Warren A. Aeolian Geomorphology: A New Introduction[M]. Hoboken, USA: Wiley Blackwell, 2019.

[4] Dong Z, Chen G, He X, et al. Controlling blown sand along the highway crossing the Taklimakan Desert[J]. Journal of Arid Environments, 2004, 57(3): 329-344.

[5] Wu Zheng. Chinese Desert and Its Management[M]. Beijing: Science Press, 2003.

[6] Zhu Zhenda, Wu Zheng, Liu Shu, et al. An Outline of Chinese Deserts[M]. Beijing: Science Press, 1980.

[7] Li Jiyan. Development Environment and Evolution Patterns of Linear Dunes in the Qaidam Basin[M]. Xi’ an: Xi’ an Jiaotong University Press, 2020.

[8] Girardi J D, Davis D M. Parabolic dune reactivation and migration at Napeague, NY, USA: Insights from aerial and GPR imagery[J]. Geomorphology, 2010, 114(4): 530-541.

[9] Tsoar H, Blumberg D G. Formation of parabolic dunes from barchan and transverse dunes along Israel’ s Mediterranean coast[J]. Earth Surface Processes and Landforms, 2002, 27(11): 1147-1161.

[10] Hanoch G, Yizhaq H, Ashkenazy Y. Modeling the bistability of barchan and parabolic dunes[J]. Aeolian Research, 2018, 35: 9-17.

[11] Reitz M D, Jerolmack D J, Ewing R C, et al. Barchan-parabolic dune pattern transition from vegetation stability threshold[J]. Geophysical Research Letters, 2010, 37(19): L19402.

[12] Wolfe S A, Hugenholtz C H. Barchan dunes stabilized under recent climate warming on the northern Great Plains[J]. Geology, 2009, 37(11): 1039-1042.

[13] Goudie A. Parabolic dunes: Distribution, form, morphology and change[J]. Annals of Arid Zone, 2011, 50(3&4): 1-7.

[14] Kumar M, Goossens E, Goossens R. Assessment of sand dune change detection in Rajasthan (Thar) Desert, India[J]. International Journal of Remote Sensing, 1993, 14(9): 1689-1703.

[15] Moosavi V, Moradi H, Shamsi S R F, et al. Assessment of the planimetric morphology of barchan dunes[J]. Catena, 2014, 120: 12-20.

[16] Zhang D, Liang P, Yang X, et al. The control of wind strength on the barchan to parabolic dune transition[J]. Earth Surface Processes and Landforms, 2020, 45(10): 2300-2313.

[17] Langford R P, Rose J M, White D E. Groundwater salinity as a control on development of eolian landscape: An example from the White Sands of New Mexico[J]. Geomorphology, 2009, 105(1-2): 39-49.

[18] Vermeesch P, Drake N. Remotely sensed dune celerity and sand flux measurements of the world' s fastest barchans (Bodélé, Chad)[J]. Geophysical Research Letters, 2008, 35(24): L24404.

[19] Levin N, Ben Dor E, Karnieli A. Topographic information of sand dunes as extracted from shading effects using Landsat images[J]. Remote Sensing of Environment, 2004, 90(2): 190-209.

[20] Ren Xiaozong, Li Jiangang, Liu Min, et al. Hydrochemical composition of natural waters and its affecting factors in the eastern Hunshandake Sandy Land[J]. Arid Zone Research, 2019, 36(4): 791-800.

[21] Yang X, Wang X, Liu Z, et al. Initiation and variation of the dune fields in semi-arid China—with a special reference to the Hunshandake Sandy Land, Inner Mongolia[J]. Quaternary Science Reviews, 2013, 78: 369-380.

[22] Liu Shulin, Wang Tao, Guo Jian. Characteristics of blown sand activities in Hunshandake Sandy Land in spring[J]. Journal of Desert Research, 2006, 26(3): 356-361.

[23] Shi Weikang, Dong Zhibao, Chen Guoxiang, et al. Discussion on the symbiosis of barchan dune and linear dune: A case study from Sahara Desert[J]. Journal of Desert Research, 2020, 40(3): 135-144.

[24] Ren Xiaozong. Graphic expression, MATLAB Implementation and Its Application for Hydrochemistry in Natural Water Bodies[M]. Xi'an: Xi'an Jiaotong University Press, 2021.

[25] Wang Jingpu, Liu Lianyou, Shen Lingling. Research of the barchan dunes movement in the MU US Sandy Land on Google Earth software[J]. Remote Sensing Technology and Application, 2013, 28(6): 1094-1100.

[26] Yang Huaijun. A Study on the Movement of Sand Dunes in the Taklamakan Desert[D]. Xi' an: Shaanxi Normal University, 2019.

[27] Yang X, Liang P, Zhang D, et al. Holocene aeolian stratigraphic sequences in the eastern portion of the desert belt (sand seas and sandy lands) in northern China and their palaeoenvironmental implications[J]. Science China Earth Sciences, 2019, 62(8): 1302-1318.

[28] Dakir D, Rhinane H, Saddiqi O, et al. Automatic extraction of dunes from Google Earth images: A new approach to study the dunes migration in the Laâyoune city of Morocco[C]//International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 2016, 42: 53-59.

[29] Yang X, Scuderi L, Paillou P, et al. Quaternary environmental changes in the drylands of China—A critical review[J]. Quaternary Science Reviews, 2011, 30(23-24): 3219-3233.

[30] Bai Xuemei, Chun Xi, Siqin Bilige, et al. Changes of lakes in Hunshandake Sandy Land in the past 45 years, Inner Mongolia[J]. Journal of Lake Sciences, 2016, 28(5): 1086-1094.

[31] Ma W, Wang X, Zhou N, et al. Relative importance of climate factors and human activities in impacting vegetation dynamics during 2000-2015 in the Otindag Sandy Land, northern China[J]. Journal of Arid Land, 2017, 9(4): 558-567.

[32] Lancaster N, Baas A. Influence of vegetation cover on sand transport by wind: Field studies at Owens Lake, California[J]. Earth Surface Processes and Landforms, 1998, 23(1): 69-82.

[33] Yang X, Forman S, Hu F, et al. Initial insights into the age and origin of the Kubuqi sand sea of northern China[J]. Geomorphology, 2016, 135(1-2): 108-116.

[34] Yang X, Scuderi L, Liu T, et al. Formation of the highest sand dunes on Earth[J]. Geomorphology, 2011, 135(1-2): 108-116.

[35] Parteli E J R, Durán O, Bourke M C, et al. Origins of barchan dune asymmetry: Insights from numerical simulations[J]. Aeolian Research, 2014, 12: 121-133.

[36] Ma Yongtao, Ren Xiaozong, Hu Huifang, et al. Vegetation dynamics and its driving force in Otindag Sandy Land based on Geodetector[J]. Journal of Desert Research, 2021, 41(4): 195-204.

[37] Cui X, Sun H, Dong Z, et al. Temporal variation of the wind environment and its possible causes in the Mu Us Dunefield of Northern China, 1960–2014[J]. Theoretical and Applied Climatology, 2019, 135(3): 1017-1029.

[38] Wang X, Zhou Z, Dong Z. Control of dust emissions by geomorphic conditions, wind environments and land use in northern China: An examination based on dust storm frequency from 1960 to 2003[J]. Geomorphology, 2006, 81(3-4): 292-308.

[39] Wilson I G. Ergs[J]. Sedimentary Geology, 1973, 10(2): 77-106.

[40] Mckee E D. Structures of dunes at white sands national monument, New Mexico (and a comparison with structures of dunes from other selected areas)[J]. Sedimentology, 1966, 7(1): 3-69.

[41] Mckee E D, Moiola R J. Geometry and growth of the white sands dune field, New Mexico[J]. Journal of Research of the US Geological Survey, 1975, 3(1): 59-66.

[42] Fryberger S G, Dean G. Dune forms and wind regime[C]//Edwin D. McKee, ed., A Study of Global Sand Seas. Washington: United States Government Printing Office, 1979.

[43] Yang Funing, Lü Ping, Ma Fang, et al. Morphological evolution and migration characteristics of reticulate dunes at southern fringe of Tengger Desert[J]. Journal of Desert Research, 2023, 43(1): 1-9.

[44] Wang Tao. Desert and Desertification in China[M]. Shijiazhuang: Hebei Science & Technology Press, 2003.

[45] Yang Junhuai, Dong Zhibao, Liu Zhengyao, et al. Aeolian geomorphology and dune migration in the Quruq Desert, China[J]. Journal of Desert Research, 2019, 39(4): 1-8.

Note: Figure translations are in progress. See original paper for figures.